Mapping the Distribution of Stars in the Milky Way

Estimating ***r*** and ***v***

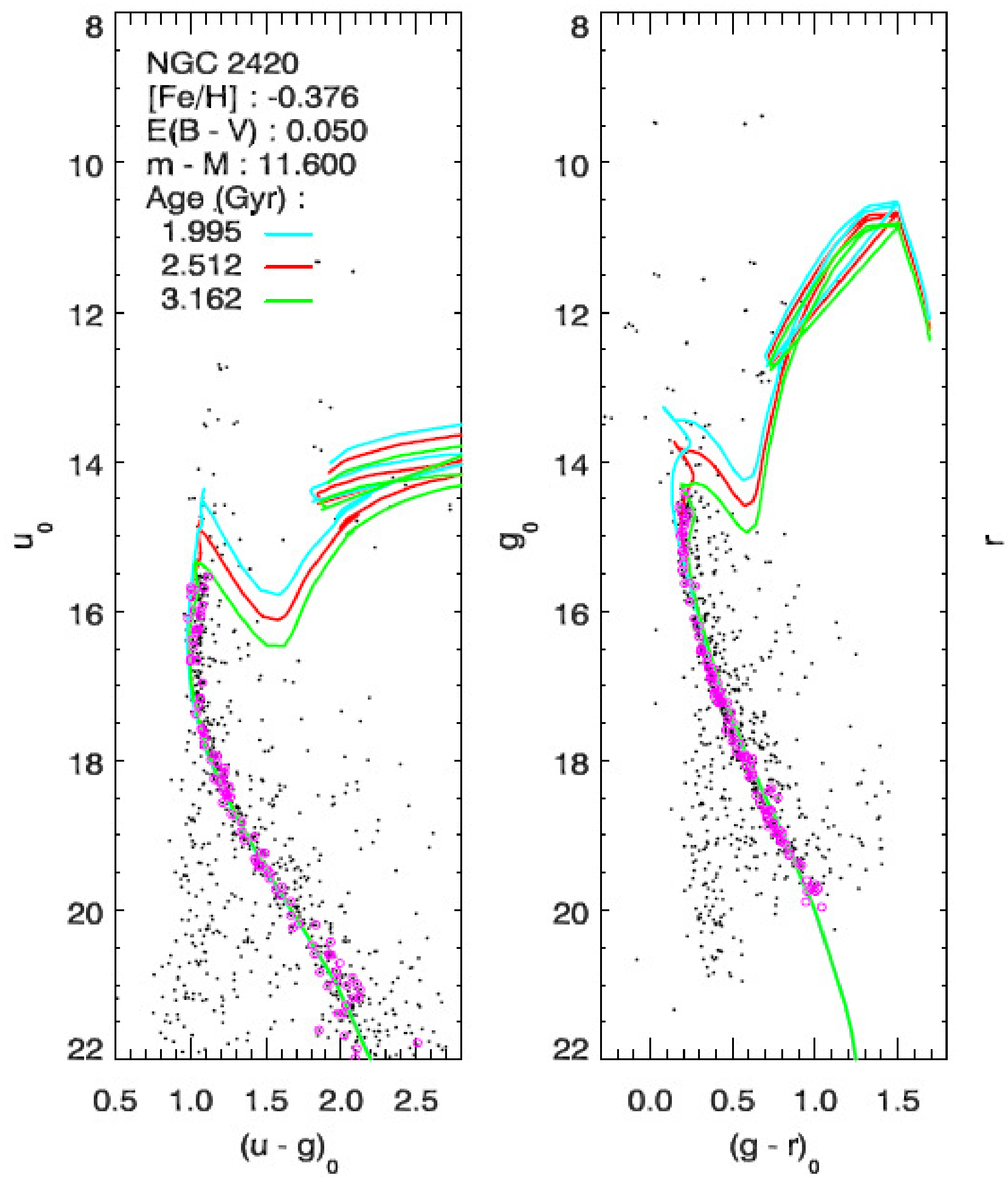
Estimating [Fe/H],[X/H],ages(?)

Fitting ‘components’ to what one sees

What is the sp

- **Geometry/kinematics**
- Other **sub-populatic**
  - Metallicity: Fe/H, [α/Fe],
  - Age:
    - Straightforward in si population, i.e. clust
    - Individual stars:
      - Upper limits on a
      - Luminosity and p

NGC 2420 CMDs



Astrometry today:

Measuring positions: α,δ and μ_α,μ_δ,

- How well can you measure the (relative) position of a star?
  - $\delta x \sim \sigma_{PSF}/(S/N)$ (King 1983)
  - E.g. δ~20 mas for FWHM=1.5" and S/N=30 (ground-based)
  - E.g. δ~1 mas for FWHM=0.1" and S/N=40 (space, e.g. HST)

- Positions *per se* can be measured exceedingly accurately

- Precision matters only for parallaxes and proper motions

Proper motion measurements

In general: $\delta\mu \sim 1.41 \times \delta_{pos}$ / time-baseline

Two relevant regimes:

incl. photographic plates to V~19.5

$$\delta\mu \sim 3\text{mas/yr}\left[\frac{2''}{FWHM}\right]\times\left[\frac{15}{S/N}\right]\left[\frac{30\,yrs}{\Delta t}\right]$$

current generation CCD surveys (SDSS, PanSTARRS1) to V~22.5

$$\delta\mu \sim 1.7\text{mas/yr}\left[\frac{0.7''}{FWHM}\right]\times\left[\frac{50}{S/N}\right]\left[\frac{4\,yrs}{\Delta t}\right]$$

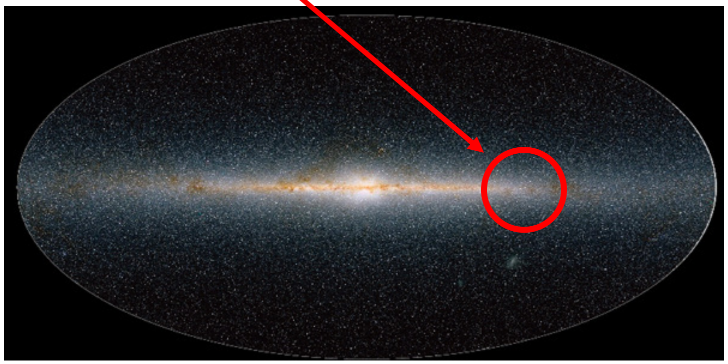
GAIA: ~20 μasec/yr at V=15 or 0.15 mas/yr at V=20

On sky velocities: the use of proper motion measurements

Current ground-based measurements: $\delta\mu$~2mas/yr

Note: Distance errors enter $\mu \rightarrow v$ conversion

→ δv~10 km/s @ D=1kpc



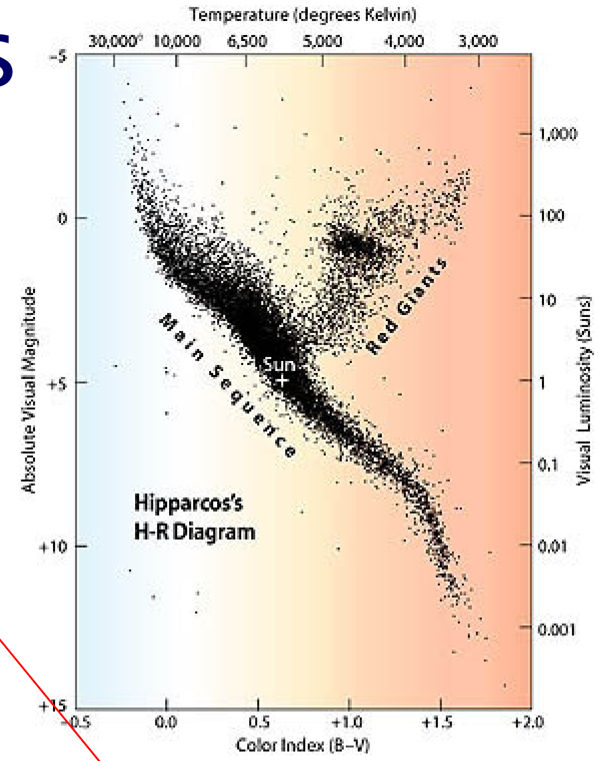
Faint stars (V=19) with GAIA: 0.08 mas/yr

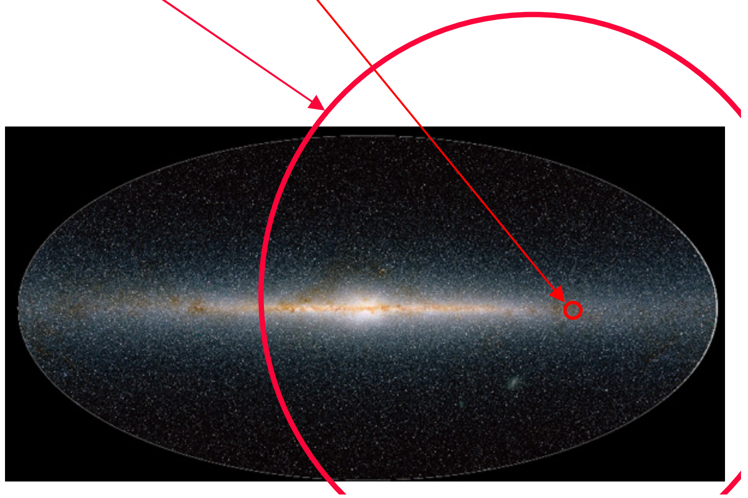
→ δv~8 km/s @ D=20kpc

Distances to individual stars

1. Parallaxes

- Hipparchos 10% accuracy @ 100pc @10mag
- GAIA: 10% accuracy @ 10.000pc @15mag





Distances to individual stars

2. Estimating intrinsic luminosities

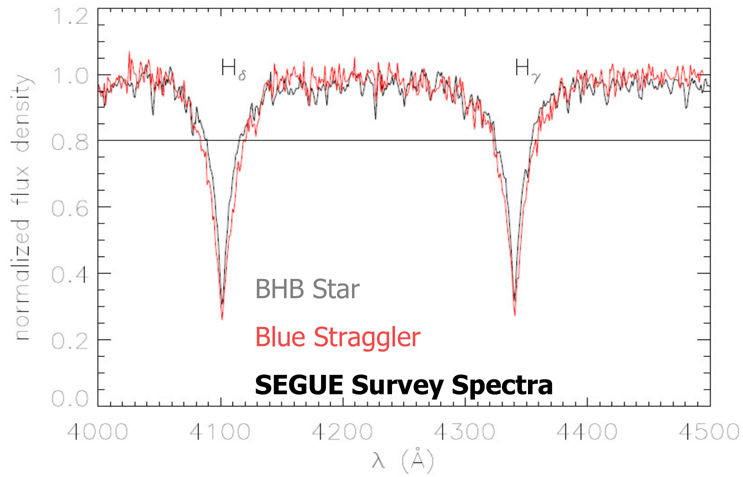
From: either spectra, colors, or light-curves

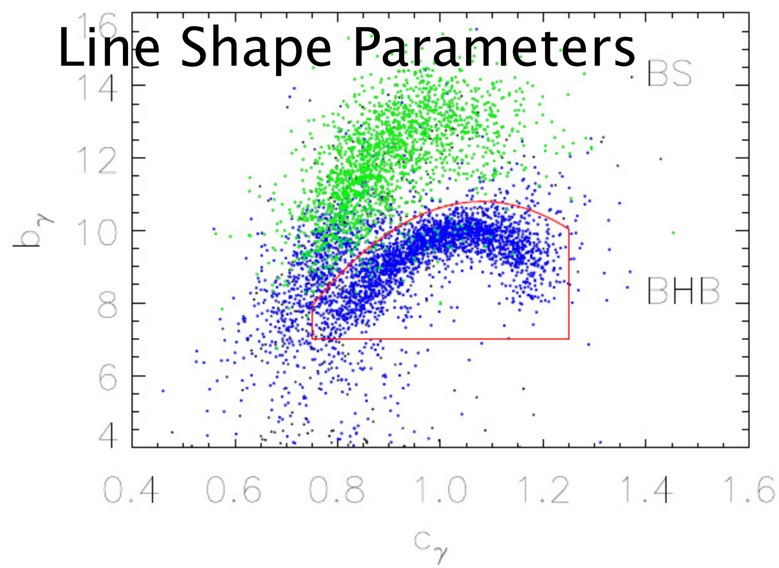
Basic classes of stars:

- **Main sequence stars:** common, L ~ color
  - In ‘old’ populations: F stars are the most luminous
- **Giants:** luminous, but hard to estimate luminosity
  - Except rare top-of-the-giant branch stars
- **Special classes:**
  - Cepheids (rare)
  - RR Lyrae and blue horizontal branch stars (BHB)
    - Both M_V~0.5; mostly metal poor

Example for "special stars": BHB stars in SDSS

- Pre-select by color, then measure Balmer line profile parameters (cf Sirko et al 2004, Xue, Rix et al 2008)
  - identification >90%
  - Distances 5-10%
  - Stars are metal poor

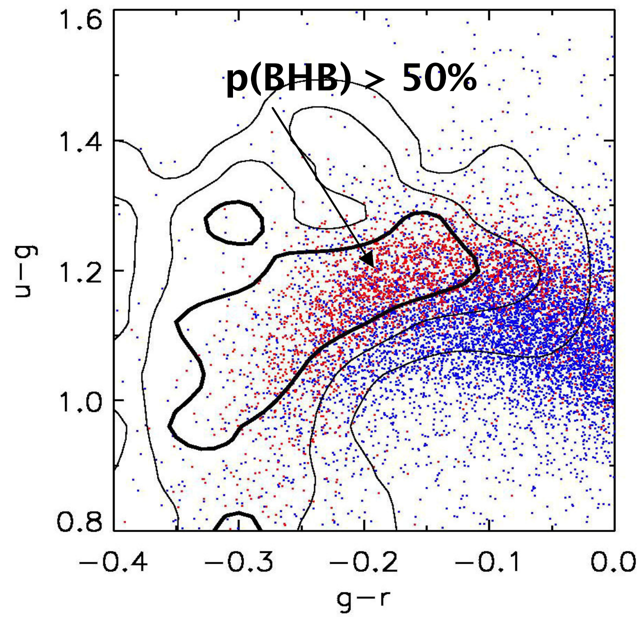




Example for "special stars": BHB stars in SDSS

- How to use spectra (on a modest set of sources) to 'train' photometric classification?

- Map spectral classification back into color-color space → vastly larger samples → 30.000 BHB stars (>50% reliable) in SDSS with 5% distances



BHB stars , non-BHB (blue stragglers)

From spectral classification

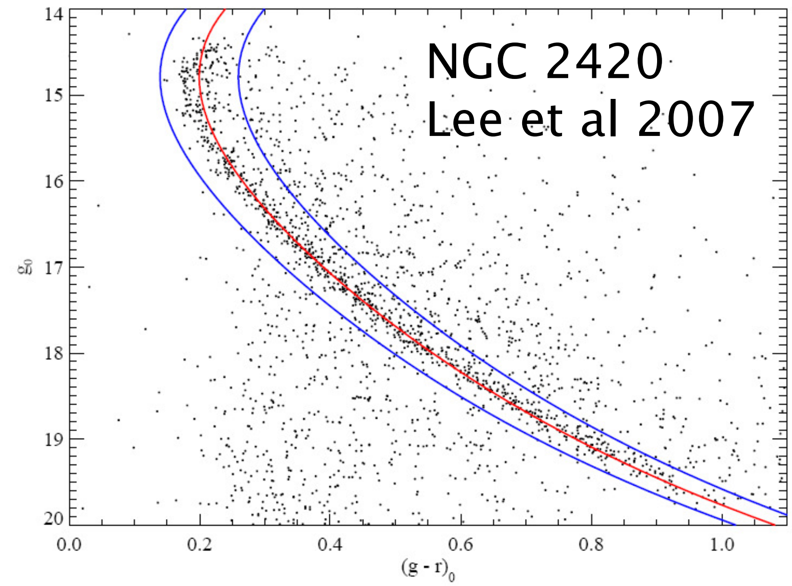
Bell et al 2009, Xue et al 2009

Distances to Main Sequence Stars

- On the main sequence, the luminosity is a strong function of the effective temperature (or color)
  - Weak dependence on age (except MS lifetime)
  - Strong (~1 mag) luminosity dependence on metallicity of the stars (line blanketing)
    - Remember ‘sub-dwarfs’?
  - Clusters are ideal laboratory for calibration
    - (known) single distance, age, and[Fe/H]

Main Sequence Distances from Photometry

a.k.a. photometric parallax
[here based on SDSS data]

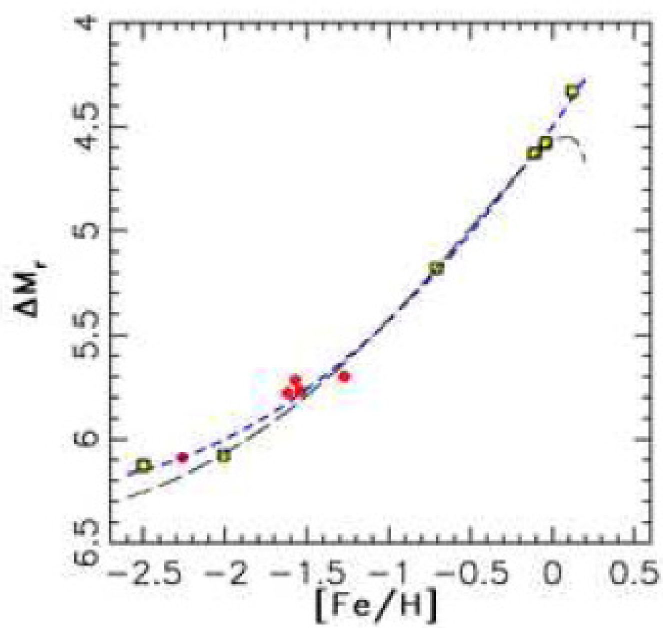


- Calibrate M_g vs (g-i) on clusters.

$$M_r^0(g-i) = -2.85 + 6.29\,(g-i) - 2.30\,(g-i)^2,$$

- Metallicity leads to an offset in this relation

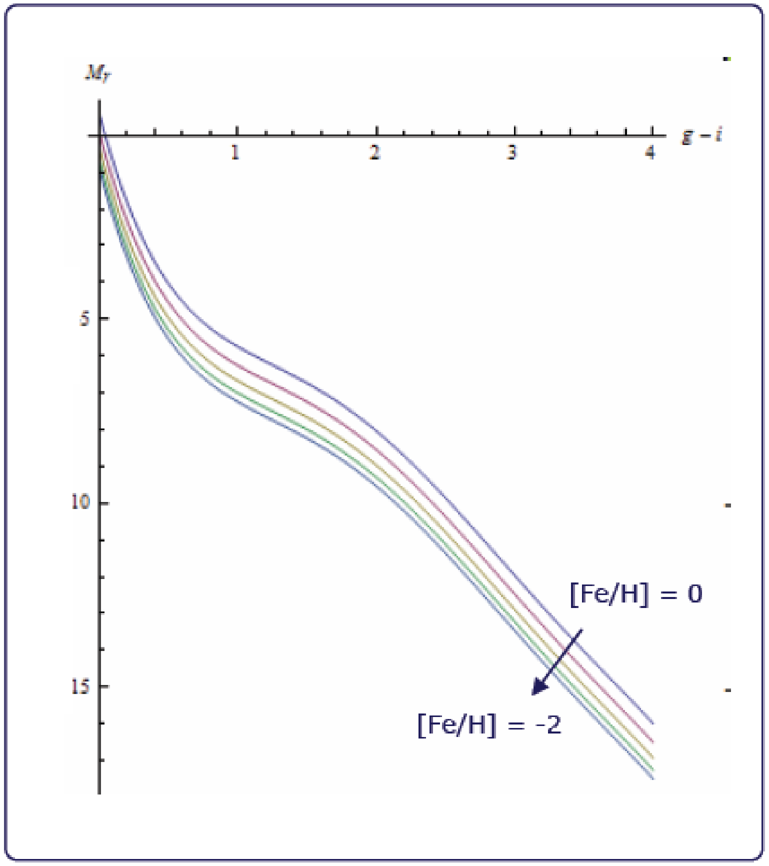
$$M_r(g-i,[Fe/H]) = M_r^0(g-i) + \Delta M_r([Fe/H])$$



- Cluster calibration indicates that if [Fe/H] is known to 0.25dex systematic distance errors ar <~10%
- Individual errors depend on photometry errors and color (worst near turn-off)
- Laird, Carney and Latham 1988
- **Ivezic et al 2007**

$$M_r(gi,0) = -0.56 + 14.32\,gi - 12.97\,gi^2 + 6.127\,gi^3 - 1.267\,gi^4 + 0.0967\,gi^5 \quad 0.3 < g - i < 4$$

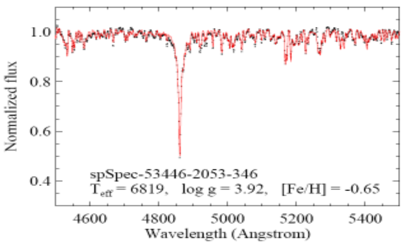
$$\Delta M_r([Fe/H]) = -1.11[Fe/H] - 0.18[Fe/H]^2 \quad -2 < [Fe/H] < 0$$

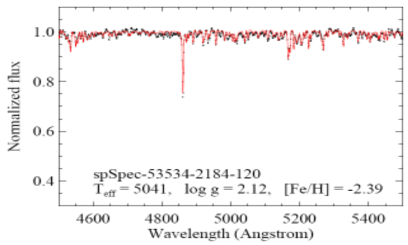


1. Metallicity-dependent photometric parallax relation for MS stars
2. Tied to globular clusters on the blue end (g-i<1)
3. Tied to Hipparcos at 1<g-i<2
4. Tied to ground-based trigonometric parallaxes for g-i>2
5. **Distance estimates to better than 15% (<u>likely better than 10% on the blue/bright end</u>)**
6. **Directly applicable to any (u)gri survey (PanSTARRS, SkyMapper, DES, LSST, …)**

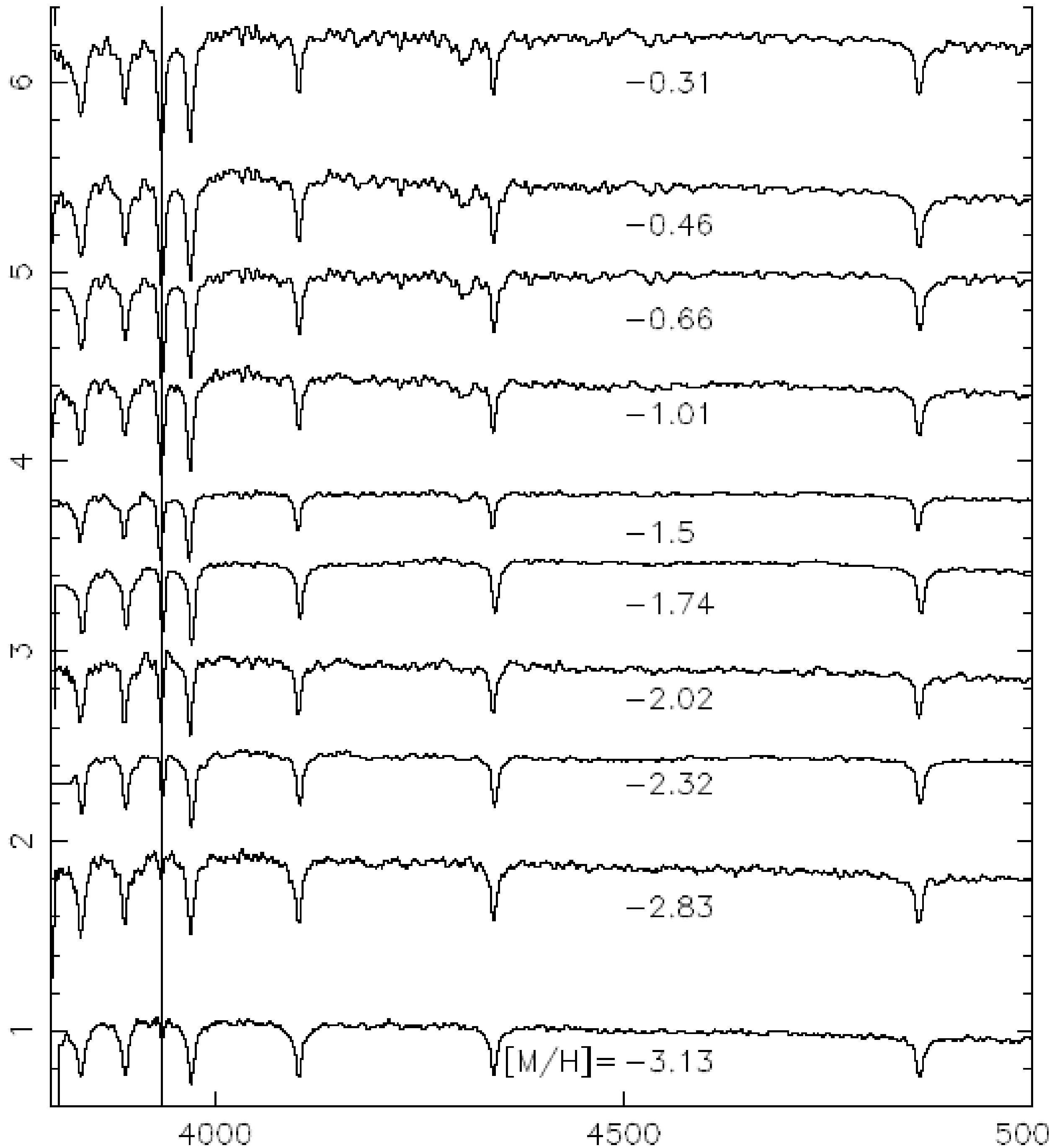
Stellar parameters from medium resolution spectra

- Determine parameters by comparison with model atmospheres (either in pixel space, or line indices)
  - **T_{eff}** : from colors and line strengths (e.g. Balmer)
  - **Log(g)** → luminosity, i.e. MS-subgiant-giant:
    - line-profiles (need resolution!)
    - Gravity sensitive lines (CO band-head in the near IR)
  - **[Fe/H]:** metal line strengths [single elements need higher resolution to isolate lines, see K. Freeman]
- Calibration in clusters and against high resolution spectra
- Example SDSS/SEGUE spectra:
  - δT_{eff}= 200k, δ[Fe/H]~0.25dex, δ[log(g)]~0.5dex
  - [Lee et al 2008,Yanny et al 200
    δv ~ 5-15 km/s



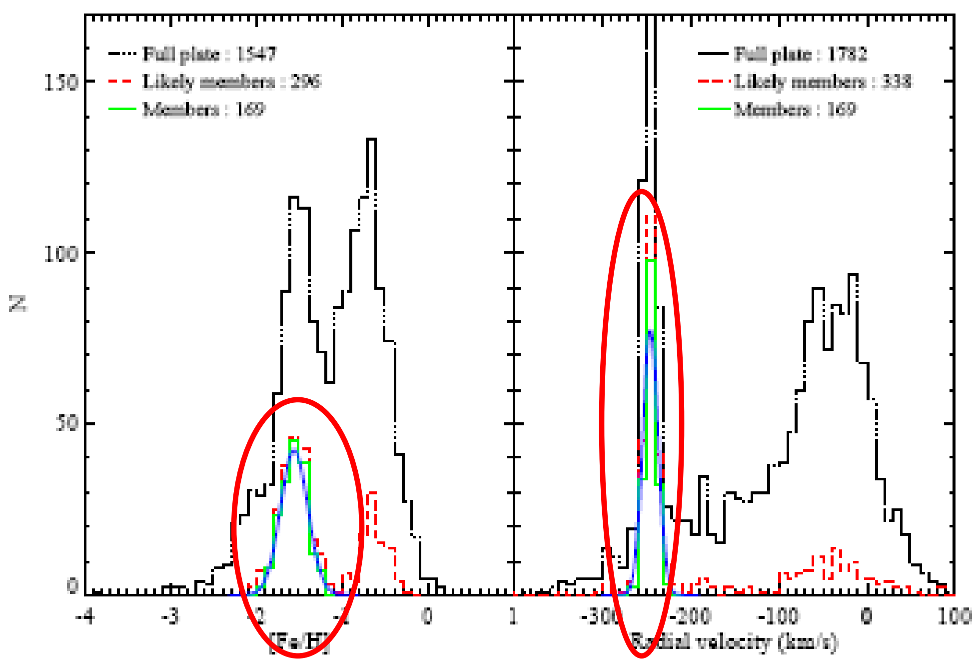


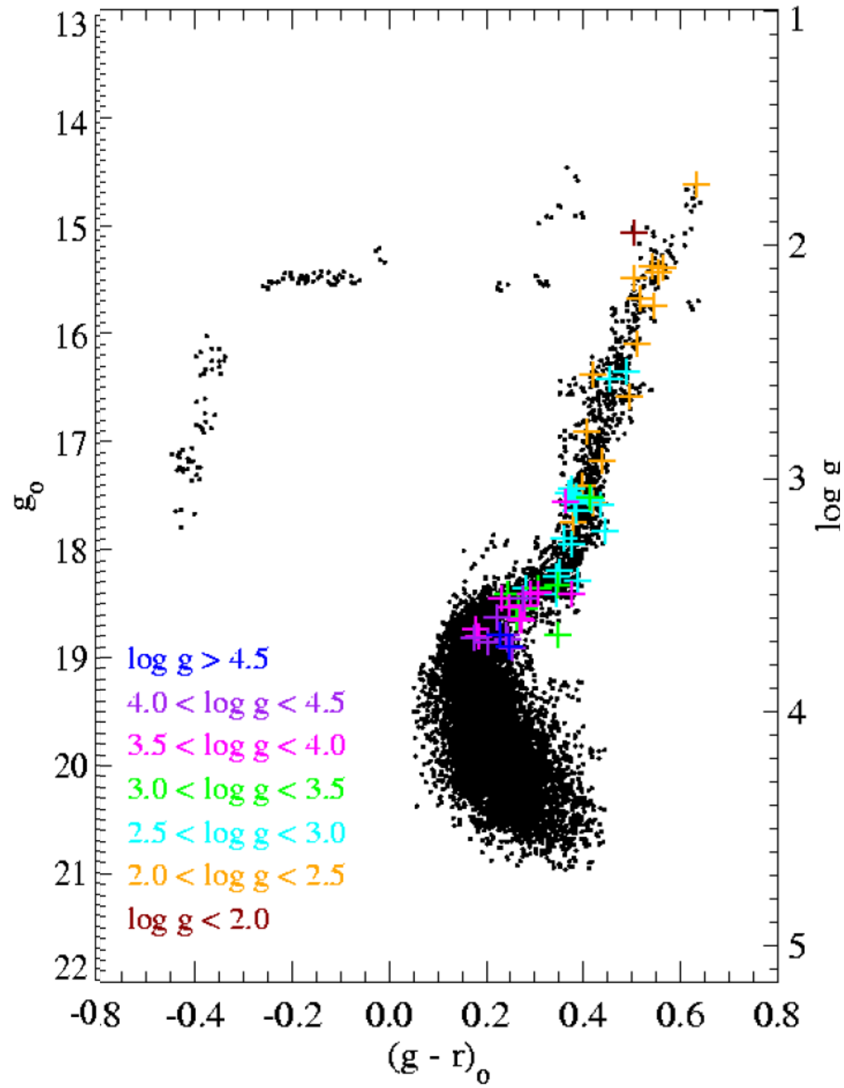
Stars of similar T_{eff} but decreasing [Fe/H]



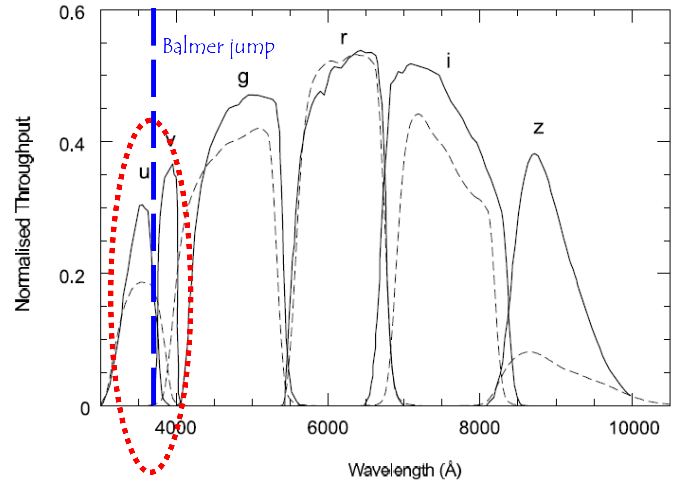
How well can you determine stellar parameters with spectra of SDSS-resolution?

- Res. ~ 2800
- Test with clusters





Stellar Parameters from Colors



- Optimize filter set for stellar parameters

- SkyMapper: Murphy et al 2008, Keller et al 2007

Stellar Parameters from Colors

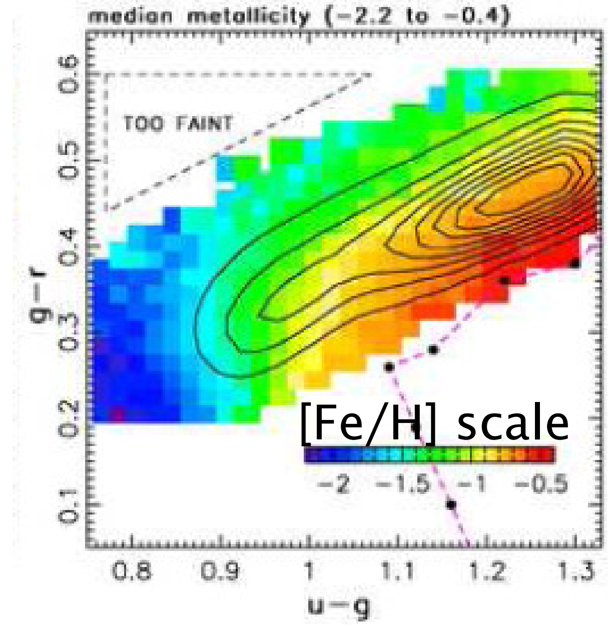
- What can be done with only broad-band filters? E.g. SDSS

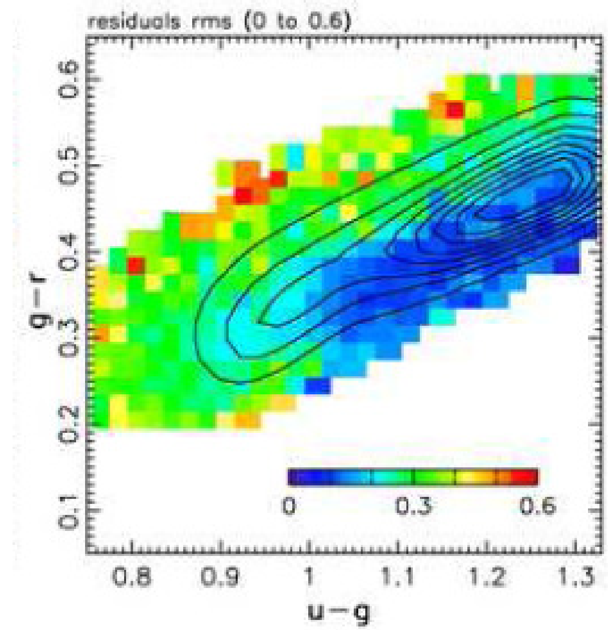
  Ivezic et al 2008

  - For stars with 5000K < T < 7000K one can estimate their metallicity from their position in the u-g g-r color-color plane
  - At least for metal-poor-ish stars (Fe/H<-0.5)
  - Accuracy: ~0.3 dex

  → **metallicity estimates for millions of stars**

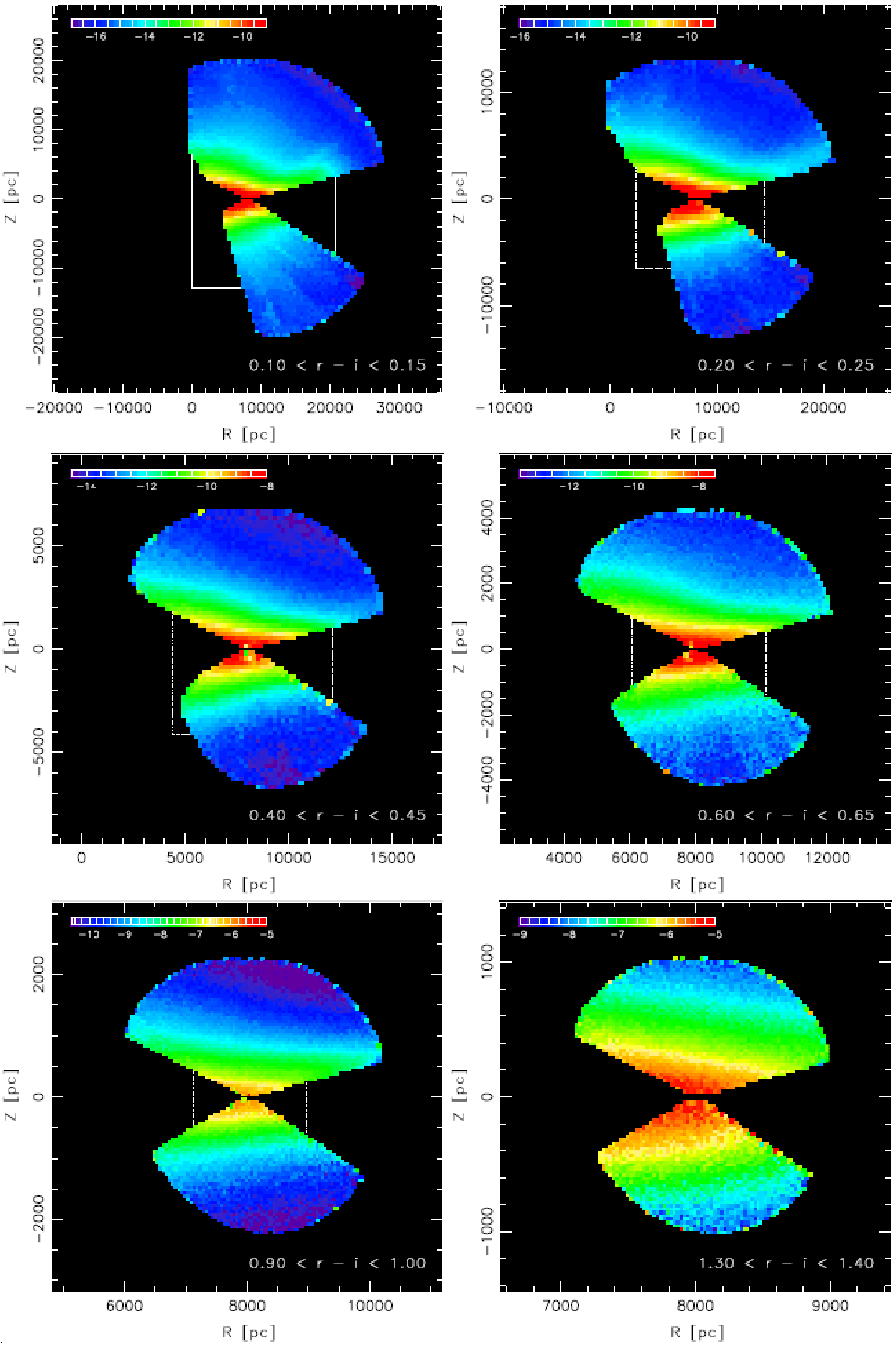
Star colors as function of [Fe/H]



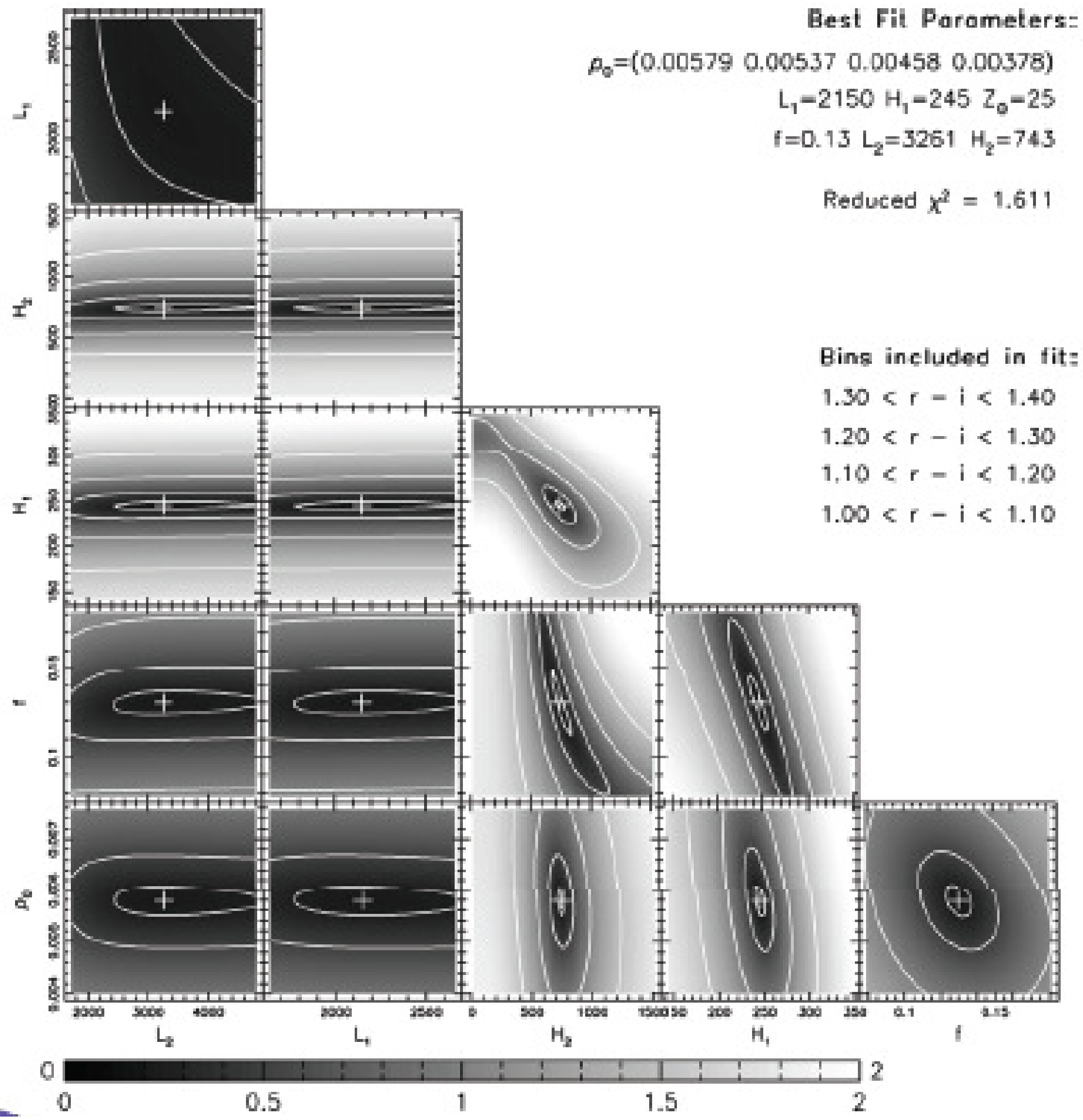


Star-by-star density maps of the Milky Way (SDSS volume)

- From Juric et al 2007
- Panels: different colors/luminosities
- Note different scales of the panels



Disk Model Fit



- M-dwarfs (D < 2 kpc) excellently fit by two exponentials
- Best fit:
  - $Z_0 = 25$ pc
  - $H_1=245$ pc, $H_2=740$ pc
  - $L_1=2.15$ kpc, $L_2=3.3$ kpc
  - $f=13\%$
  - Reduced $\chi^2=1.6$
- Uncertainties and covariances easily seen in χ^2 plots (left)
- Same values obtained when allowing the scales to vary in adjacent color bins

Summary

- ‘Classic’ tools to estimate stellar properties, distances, motions, etc.. are back *en vogue*
  - Spectroscopy for precision
  - Photometry for mass production

- 10% distances to >10^7 stars, metallicities for 10^6 stars exist.

- We can make 3D star-by-star or population maps of (good parts of) the Milky Way
  - You can practice now for GAIA